Journal of Magnetism and Magnetic Materials 201 (1999) 285–289

Journal of magnetism and magnetic materials

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Magnetic field effects in the impact of a magnetic fluid drop

S. Sudo[a,]*, N. Wakamatsu[a], T. Ikohagi[b], H. Nishiyama[b], M. Ohaba[c], K. Katagiri[b]

[a]*Department of Mechanical Engineering, Iwaki Meisei University, Iwaki 970-8551, Japan*
[b]*Institute of Fluid Science, Tohoku University, Sendai 980-8577, Japan*
[c]*Faculty of Engineering, Toingakuen University of Yokohama 225, Japan*

Received 20 May 1998; received in revised form 25 August 1998

Abstract

The impact phenomena between a magnetic fluid drop and paper on the hard rubber mat, subject to a magnetic field, have been investigated. Effects of a magnetic field on the spread area of a magnetic drop and on the velocity of radial flow were revealed with a three-dimensional motion analysis system. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Magnetic fluids; Impact phenomena; Magnetic drops

1. Introduction

The study of the impact phenomena of a liquid drop is of fundamental interest and importance in various fields. Therefore, the various phenomena which occur when a drop of water strikes a water surface have been studied by a number of researchers [1]. Furthermore, the collision between a liquid mass and a solid surface has also been studied by a number of researches [2]. The subsurface phenomena and the splashing impact of magnetic liquid drops against kerosene, with or without applied magnetic fields, were investigated by Sudo et al. [3]. However, no study has been published on the impact phenomena of a magnetic fluid drop on the plane solid surface under an applied magnetic field.

The purpose of the present paper, therefore, is to investigate the impact phenomena between a magnetic fluid drop and paper on the hard rubber mat under applied magnetic fields, and to clarify the splashing characteristics. Effects of applied magnetic fields on the magnetic fluid–solid surface impact are revealed.

2. Experimental apparatus and procedures

A schematic diagram of the experimental apparatus is shown in Fig. 1. Magnetic fluid drops were formed with a 25 ml burette. The drops were made to fall through the beam of a laser and the hole of a drop cutter [3]. The drops of magnetic fluid fell on a piece of paper that was bonded to the hard rubber mat. The impact velocity of the drop was varied by the change of the height from which it fell. A permanent magnet installed under the rubber

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* Corresponding author. Fax: + 81-246-29-0577.
E-mail address: sudou@iwakimu.ac.jp (S. Sudo)

PII: S0304-8853(99)00029-3

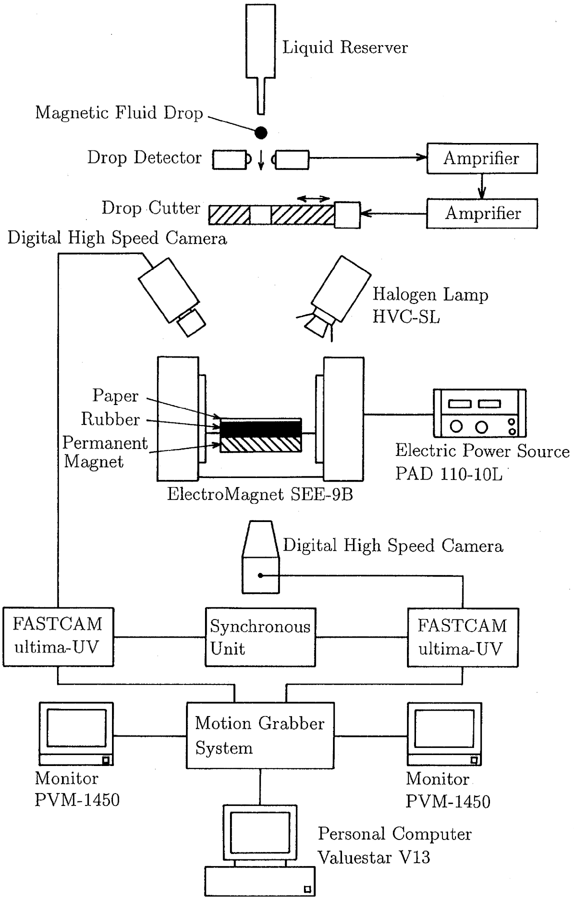

Fig. 1. Schematic diagram of experimental apparatus.

mat was used to magnetize the magnetic drop (the direction of an applied magnetic field is perpendicular to the target plane), or an electromagnet was used (the direction of an applied magnetic field is parallel to the target plane). The impact phenomena of magnetic fluid drops were analyzed by a three-dimensional motion analysis system. The impact phenomena were recorded at 13 500 frames per second. A series of frames of the phenomena were analyzed by the motion grabber and a personal computer. Sample magnetic liquid used in the experiments was water-based ferricolloid W–35 (density: 1385.0 kg/m^3, viscosity: 0.0141 Pa s, surface tension: 0.0294 N/m at a temperature of 20°C).

3. Experimental results and discussion

3.1. *General impact phenomena without a magnetic field*

Studies of liquid drops splashing on solid surfaces were initiated by Worthington. Recently, attention has been directed at the pressure developed on impact and the spread of the liquid over the solid surface, because the collision between a liquid mass and solid can generate high transient pressures and cause significant damage. The pressures generated during a liquid–solid impact have been given by Dear and Field [4] as

$$P = \frac{v\rho_1 C_1 \rho_2 C_2}{\rho_1 C_1 + \rho_2 C_2}. \tag{1}$$

The main features of splashing on rough solid surfaces have been revealed by Levin and Hobbs [5]. However, common liquids are not sensitive to changes in magnetic field. Therefore, the emphasis in our study of the hydrodynamics of impact phenomena is to note the effect of a magnetic field when there is an impact between a magnetic fluid drop and a paper surface.

3.2. *Impact phenomena with a perpendicular magnetic field*

Fig. 2 shows a sequence of photographs of the interfacial phenomena produced by a magnetic fluid drop after it had fallen through a vertical height $H = 0.3$ m and colloided with the paper pasted on the rubber mat under a perpendicular magnetic field to the target surface. In Fig. 2, B is the magnetic flux density, and the stage which is nearest to the first instant of contact between the drop and the target, is marked as $t = 0$ s. After drop impact, the liquid flows radially outward from the underside of the drop to form a thin liquid layer on the paper surface. As the drop collapses, the liquid layer increases in area and a number of spikes are formed by a perpendicular magnetic field. It was found that the number of spikes depends on the magnetic field's strength and the impact velocity of the drop. Firstly, magnetic fluid spikes are formed at the periphery of the spread area, and follow the

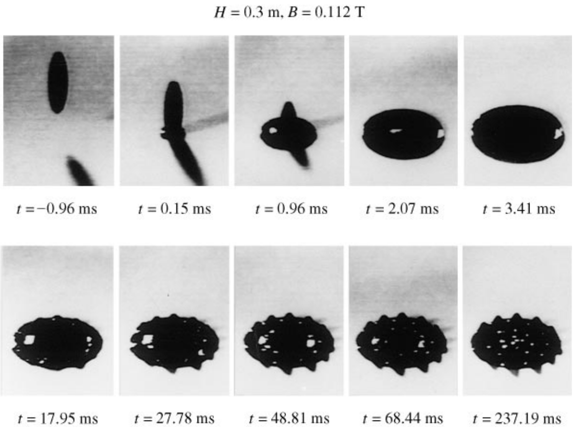

Fig. 2. Photographs of a sequence of stages in the impact.

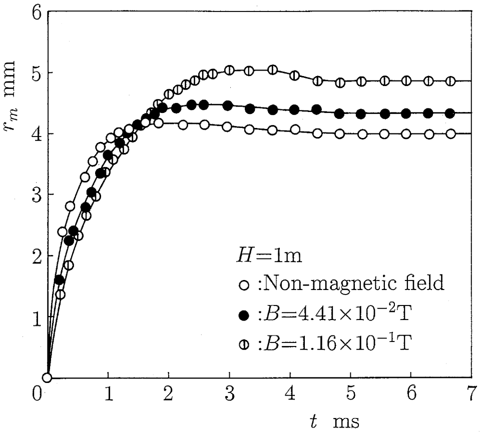

Fig. 3. Radius of the base of the magnetic fluid spread.

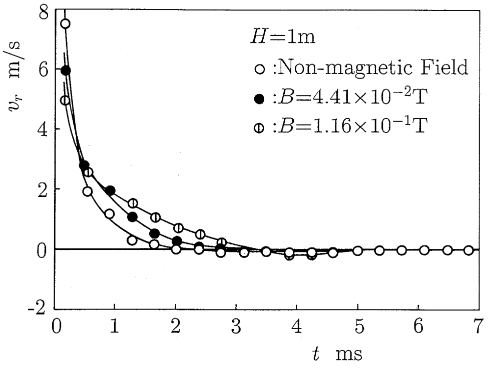

Fig. 4. Radial flow speed of magnetic fluid.

inside. Finally, the interfacial system reaches its equilibrium state.

Fig. 3 shows how the radius of the base of the magnetic fluid spread varies with time measured from the moment of impact. The radius initially increases rapidly but then the velocity of spread over the paper surface gradually decreases. At higher magnetic flux densities, the radius of the base of magnetic fluid spread, r_m, slowly increases, and may finally enlarge. That fact is due to the magnetic drop deformation produced by an applied magnetic field. The following inference can be drawn from the drop deformation. The transient pressure generated during the impact under the perpendicular magnetic field can get larger than Eq. (1) in the case of a nonmagnetic field.

Fig. 4 shows how the radial flow speed of magnetic fluid varies with time. The impact velocity at the fall distance $H = 0.3$ m is $v = 2.21$ m/s without a magnetic field. It can be seen from these results that the initial radial flow speed of the base of the magnetic fluid spread, v_r, is about an order of magnitude greater than the impact velocity. This is a consequence of the pressure which builds up in the drop after impact [5]. However, the initial high velocity of spread decays very fast and reaches a value of zero within about 2 ms under a nonmagnetic field. On the other hand, the velocity v_r under the magnetic field slowly reaches a value of zero.

3.3. *Effect of perpendicular magnetic field on the radial flow*

As was stated previously, the applied magnetic field has an effect on the radius of the base of the magnetic fluid spread, r_m, and the radial flow velocity v_r. The experimental results obtained are described by the following equation:

$$\frac{2r_m}{d} = \alpha \, \mathrm{Re} \, L(\gamma), \tag{2}$$

where

$$\mathrm{Re} = \frac{vd}{\nu} \quad \text{(Reynolds number)},$$

$$L(\gamma) = \coth \gamma - \frac{1}{\gamma} \quad \text{(Langevin function)},$$

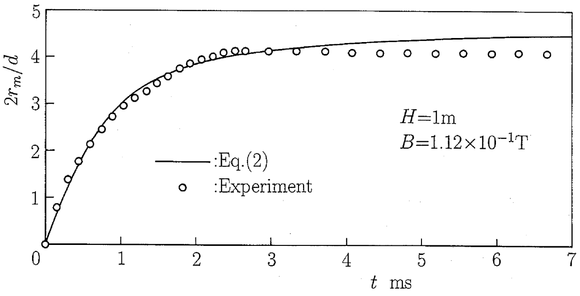

Fig. 5. Comparison between experimental result and Eq. (2).

$$\gamma = \beta T_\mathrm{d} \exp\left(-\frac{M}{M_\mathrm{s}}\right) \quad \text{(Langevin parameter)},$$

$$T_\mathrm{d} = t/\left(\frac{V_\mathrm{d}}{S_\mathrm{d} v_\mathrm{o}}\right) \quad \text{(dimensionless time)},$$

d is the drop diameter, ν the kinetic viscosity, M the magnetization, M_s the saturation magnetization, V_d the drop volume, S_d the surface area of the drop, v_o is the impact velocity without a magnetic field, and α and β are the experimental constants. Fig. 5 shows an example of the comparison of the experimental results with Eq. (2).

3.4. *Effect of magnetic field on the impact mark*

After a magnetic fluid drop impacts a paper surface under a perpendicular field, an impact mark is formed. Fig. 6 shows the patterns left by drops of magnetic fluid after they had fallen onto horizontal paper under a perpendicular magnetic field. It can be seen that there are many spikes on the patterns. The formation of spikes is due to the growth of the surface instability. A topological instability on a horizontal plane layer of magnetic fluid situated in a homogeneous magnetic field perpendicular to the free surface was investigated by Barkov and Berkovskii [6]. They showed that the critical values of the dimensionless magnetization, M/M_s, of the fluid at which breakup of the volume occurs, is shown as a function of the dimensionless thickness of the layer:

$$\frac{M}{M_\mathrm{s}} = \varepsilon h \left(\frac{\rho g}{\sigma}\right)^{1/2}. \tag{3}$$

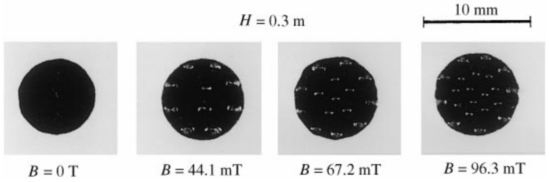

Fig. 6. Patterns left by drops of magnetic fluid under a perpendicular magnetic field.

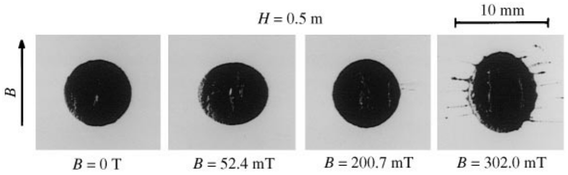

Fig. 7. Patterns left by drops of magnetic fluid under a tangential magnetic field.

It was observed that the number of spikes depends on the impact velocity too. The number of spikes increases with the impact velocity at a constant magnetic field.

On the other hand, in the case of a magnetic field tangential to the target surface, no spikes were observed on the impact pattern. Fig. 7 shows the patterns left by drops after they had fallen onto horizontal paper under a tangential field. In this case, a strange mark is observed at $B = 52.4$ mT. In general, the magnetic liquid drop elongates along the magnetic field. The experimental result shows that the liquid easily flows in the direction perpendicular to the magnetic field.

4. Conclusions

1. The maximum diameter of the magnetic fluid spread increases with the applied magnetic field perpendicular to the target surface. The radial flow velocity of the magnetic fluid spread depends on the magnetic field strength. The number of spike depends on both the magnetic field strength and the impact velocity.
2. In the case of a magnetic field tangential to the target surface, no spikes are formed on the impact pattern. The impact process ceases in the

short period compared with the case of the perpendicular magnetic field.

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